REPORT No. 146.

THE SIX-COMPONENT WIND BALANCE.

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INTRODUCTION.

For the prosecution of wind-tunnel research and testing, it is useful to have an aerodynamic balance capable of rapid and accurate measurement, in three dimensions, of the air forces and moments on a model. By authorization of the Chief Constructor, United States Navy, therefore, such a balance was devised and built in the Construction Department, Washington Navy Yard, and in June, 1920, was installed in the 8 by 8 foot tunnel. This report to the Chief Constructor of the Navy, dated August 12, 1921, was submitted for publication to the National Advisory Committee for Aeronautics by the Bureau of Construction and Repair. For temporary reference in subsequent reports, the balance is briefly described in the following pages.

DESIRABLE ELEMENTS.

The instrument was to be planted on the floor of the observation room, just over the tunnel. From experience with the preceding Eiffel balance, it seemed well to support the wind model at or near its centroid, by means of a holder easily joining it to the bottom of a single vertical shank running from midstream up through a wind shield to the main part of the balance in the room above. By convenient mechanism at his desk, the observer should be able (1) to set the model quickly and accurately in roll, pitch, and yaw without stopping the wind; (2) to measure directly and independently the drag, side drag, and lift, also the rolling, pitching, and yawing movements; (3) to have at hand automatic or self-recording devices for indicating the magnitude of these six components, perhaps also have devices for slowly and continuously varying the incidence in roll, pitch, or yaw; (4) to permit regulated oscillations of the model in roll, pitch, and yaw for determining its damping coefficients. The holder, fastened to the model before entering the tunnel, should be capable of prompt attachment to the shank inside the tunnel, without disturbing the natural flow about the model, and of prompt removal.

GENERAL EXTERIOR DESCRIPTION OF THE BALANCE.

Figures 1 and 2 give a general outside view of the balance in working order; and figure 6 is an assembly drawing. Above an all-metal desk, which serves as a base, are shown three individual weighing beams, X, Y, Z, for measuring drag, side drag, and lift; a weighing beam N for yaw; and a single weighing beam, L, M, for roll and pitch, which is set across stream for roll and along stream for pitch.[1] The mechanism through which the air force actuates these beams, and the means for setting the model in roll, pitch, and yaw will be explained later in this account. The automatic means for continuously changing the incidence and for recording forces and moments, and the oscillation devices, will be described in a detailed report to be issued later. The chief dimensions may be inferred from the linear scales in the assembly view, Figure 6.

For the present it may be remarked that the components X, Y, Z, L, M, N of the air wrench on the model are weighed directly and independently. All but one of the weighing beams are motor operated and practically identical in design. Though the yaw-beam motor was omitted for temporary convenience, it is an integral part of the design and is to be

[1] When the model sets normally these six components, X, Y, Z, L, M, N, are square with the tunnel: when it yaws L and M turn with it, the others remaining fixed.

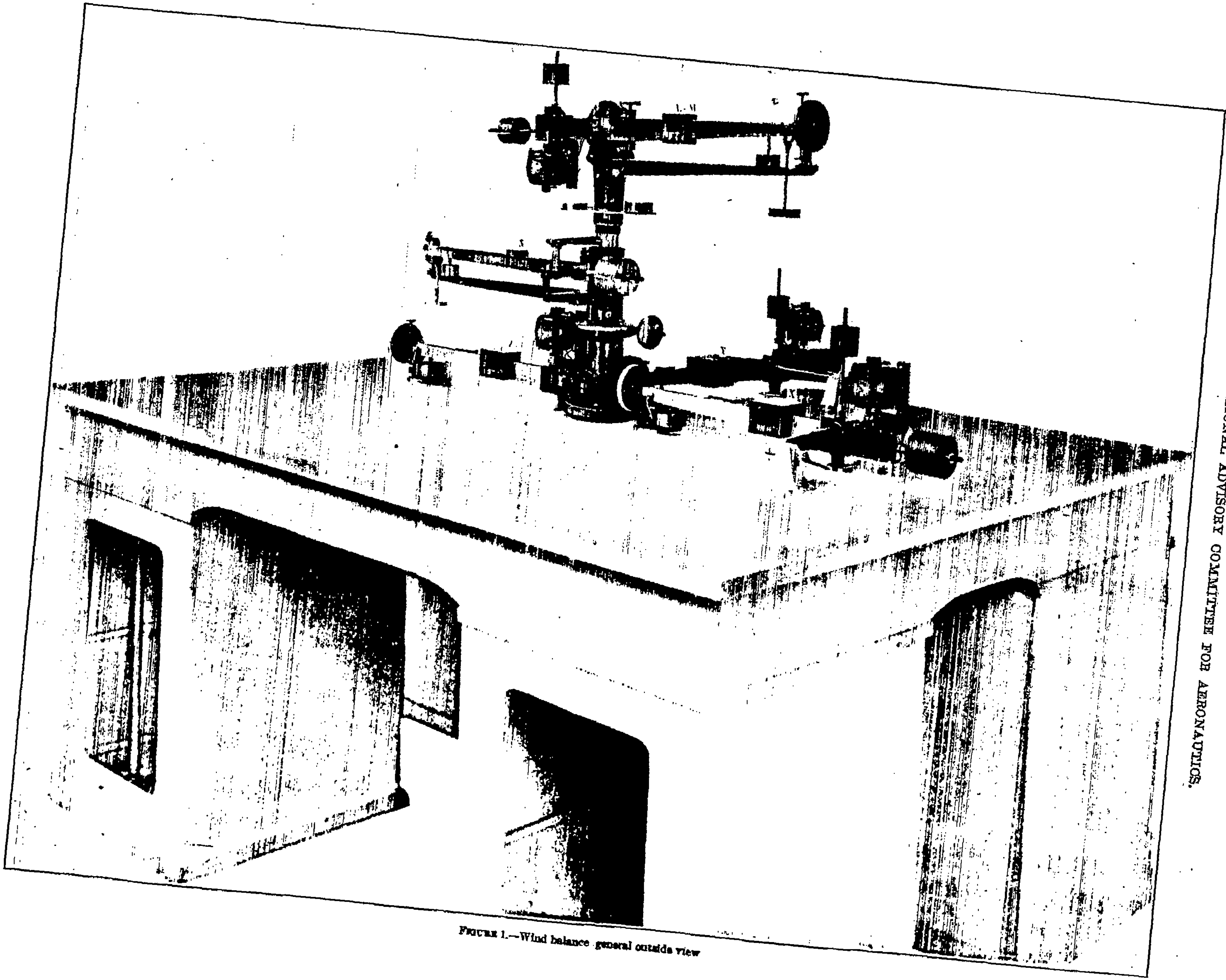


FIGURE 1.—Wind balance general outside view

installed presently. Except for one case, each weighing can be made without disturbing any of the others. The pitch motor, when accelerating, can disturb the yaw weighing, which it could not do if mounted with its axis horizontal, say, parallel to the pitch beam. Each motor is mounted with its shaft normal to the supporting knife-edge of the weighing beam, to avoid making the latter kick when the armature accelerates.

The drag and side drag beams are supported on elastic, the others on plain knife-edges. The elastic kind would be preferable in all five cases to insure against sliding or creeping. They are always clean, and are virtually frictionless for the extremely small distortions—less than 0.01°—they sustain in practice.

A description of one automatic weighing beam will serve for all. Consider, for example, the lift beam *L*, Figure 6. Along a groove in its top extends an accurate lead screw which

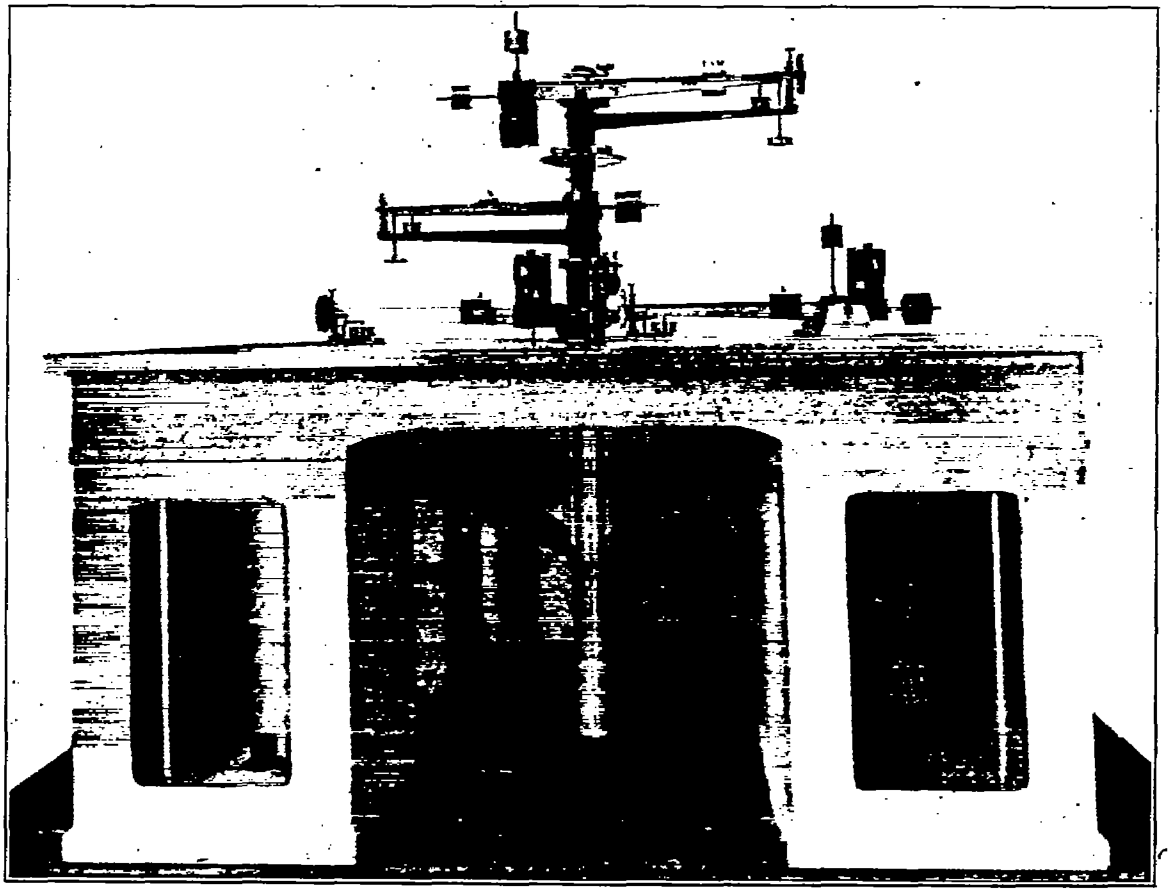


FIG. 2.—Wind balance, front view.

propels a sliding weight, without backlash, and bears at its far end a micrometer disk, at its near end a worm wheel actuated by a small motor with double-wound field. This motor rides on the beam and drives the worm wheel by means of a worm on the armature shaft. The beam vibrates a thousandth of an inch each way at its tip, between tungsten electric stops so connected as to run the motor forward with upper contact, backward with lower, and not at all without contact. Usually a 110-volt direct current line wire feeds the motor, which is of 0.005 horsepower.

The gearing and graduations are decimal. Each rotation of the motor moves the screw through 0.01 of a turn, and advances the sliding weight 0.001 inch. The advance of the sliding weight through its possible range of 10 inches is indicated in inches and tenths by the scale on the beam; in hundredths and thousandths by the scale on the micrometer disk, which latter has 100 small divisions 0.1 inch apart. On all the force beams the graduations and sliding weights are so dimensioned as to indicate air forces in pounds and decimals to one-thousandth; on the other beams air moments are indicated in pounds-inches and decimals to one-thousandth. Each weighing beam is provided with a scale pan, tare, counterweights, both sliding and threaded as shown, and an oil-damping cup with adjustable diaphragm. The mass of the sliding weight is optional; usually it moves 1 inch to weigh 1 pound or pound-inch. In these units, weighings up to 10 by increments of 0.001 are made automatically.

In Figure 3 is shown a holder with two stream-line prongs for supporting a model from the lower tip of the shank coming down from the balance. The shank is incased in a stream-line wind shield made transparent at the bottom to disclose the lower pivot detailed in Figure 7. The overhead mechanism for adjusting the holder in roll, pitch, and yaw, and for transmitting

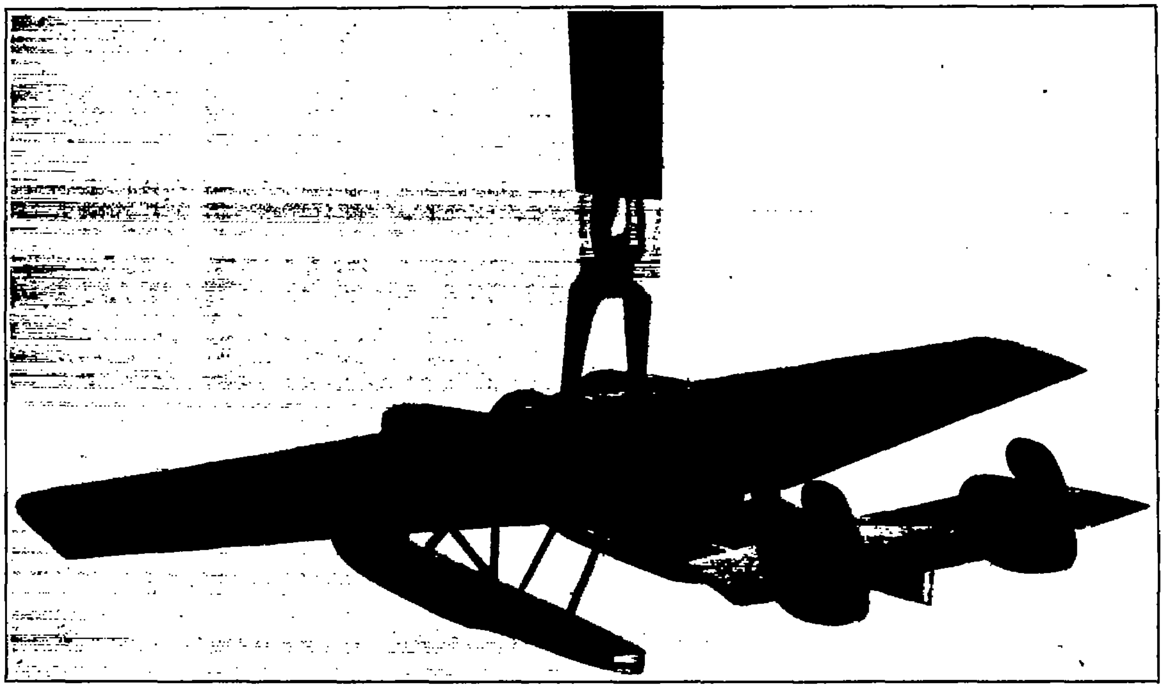


FIG. 3.—Wind balance shank, and holder attached to model.

to the weighing beams the six components X, Y, Z, L, M, N of the air wrench on the model, will next be explained.

TRANSLATION MECHANISM.

Since the lift, drag, and side force are to be measured each directly and independently of the others, the rigid framework which carries the model-bearing shank must be capable of some slight translation parallel to each of these forces.

Figure 4 delineates the chief external parts of this translation mechanism. A skeleton rectangular pyramid of cast aluminum, with its base upward, is supported at its four outer corners by four elastic vertical posts which permit it to shift freely along and across stream; also to rotate in yaw unless restrained. Inside the long vertical core *a* of this "floating pyramid" is driven a steel extension pipe *b*, which might as well be a part of the same casting. The pyramid, the large pipe, and a cast aluminum cross arm *c* firmly fixed to the lower end of the pipe form a single rigid body having, when unrestrained, three degrees of freedom in a level plane. The four supporting posts are thick drill rods nearly sawed off at their top and bottom to make them elastic along and across stream.

Inside this "floating pipe" is a coaxial "lift pipe" *e*, slightly longer and guided in vertical translation by four taut horizontal elastic rods at its bottom and four at its top. The four top guide rods are anchored to the outer corners of the pyramid, and run thence normally into the walls of the lift pipe, to which they cling by their heads like bicycle spokes. The four lower guide rods join the extremities of the floating pipe cross arm *c* to the extremities of a like cross-arm *d* firmly fixed to the bottom of the lift pipe. All these elastic guide rods, which must have the same coefficient of expansion as the castings, are held taut and horizontal by suitable tension nuts, so as to guide the lift pipe without supporting it.

To support the lift pipe a casting *f*, Figure 5, is fixed to its top with a lug on either side resting upon knife edges, shown on the inner end of the forked lift beam. The fulcrum for the lift beam is a forked casting *g*, which forms the top center of the pyramid. The lift pipe, which

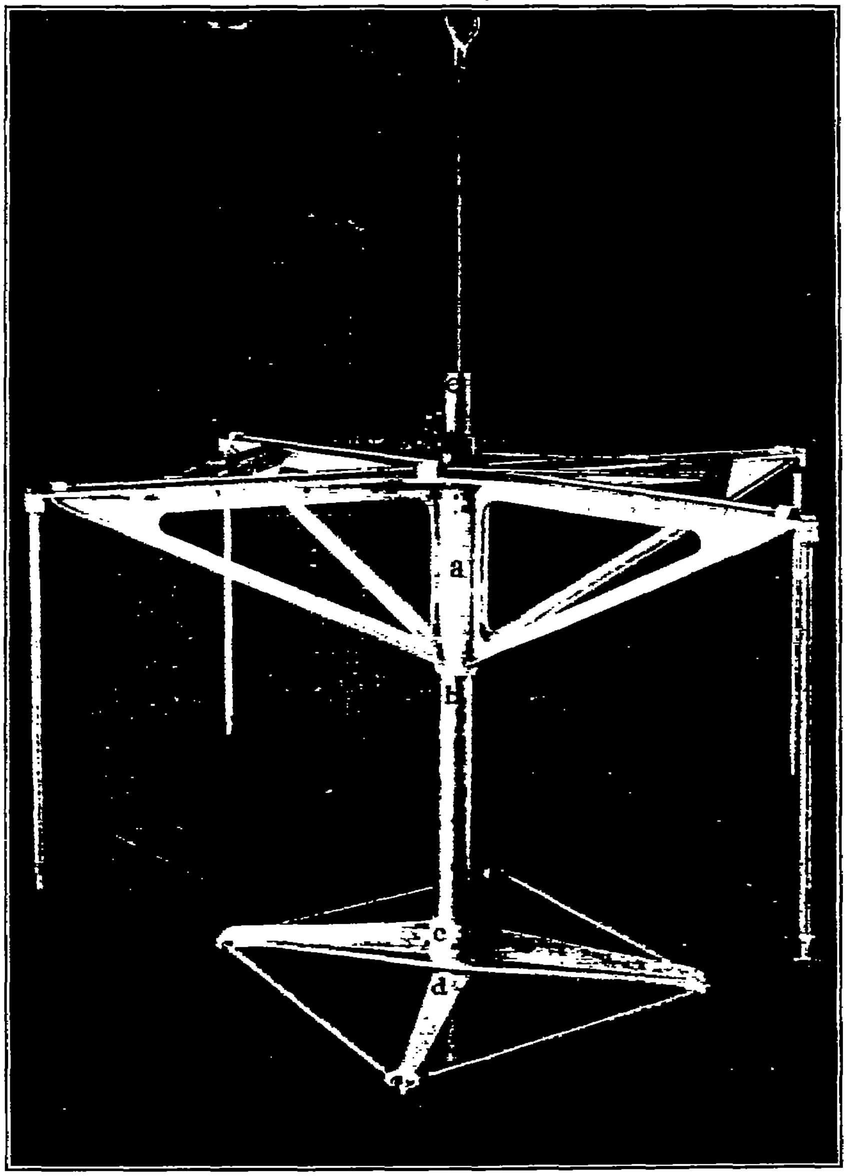


FIG. 4.—Wind balance translation mechanism.

runs down to, but does not penetrate, the tunnel roof, supports in turn the firm model-bearing shank, through intermediate mechanism to be described presently under the caption "Rotation mechanism."

The whole translation structure, just described, "floats" within the metal desk shown in Figures 2 and 6, and has its posts securely planted on laterally shiftable flat pedestals screwed to the bottoms of the four desk columns. These columns have each a leveling screw resting on a secure foundation bridge just above the tunnel ceiling.

MEASUREMENT OF LIFT, DRAG, AND SIDE DRAG.

As already explained, the lift is measured with a simple weighing beam like a steelyard. The outer tip of the lift beam, when alternately knocking the electric stops, plays about one-thousandth of an inch above and below its mean position. Then the lift pipe, resting on its other end, rises and falls about one nine-thousandth of an inch, carrying with it the mechanism supporting the shank and model. When in free balance the lift pipe vibrates up and down hundreds of times before coming to rest, though it must slightly flex at their two end necks all of the eight elastic guide rods. For all practical purposes the motion is perfectly frictionless.

The drag is measured with a bell crank whose axle is supported on two elastic knife-edges set into the two cast pillow blocks shown at the right of figures 1 and 6. From this axle two fingers or cranks h, near its ends, run down through the desk top to two long pull rods tensioned

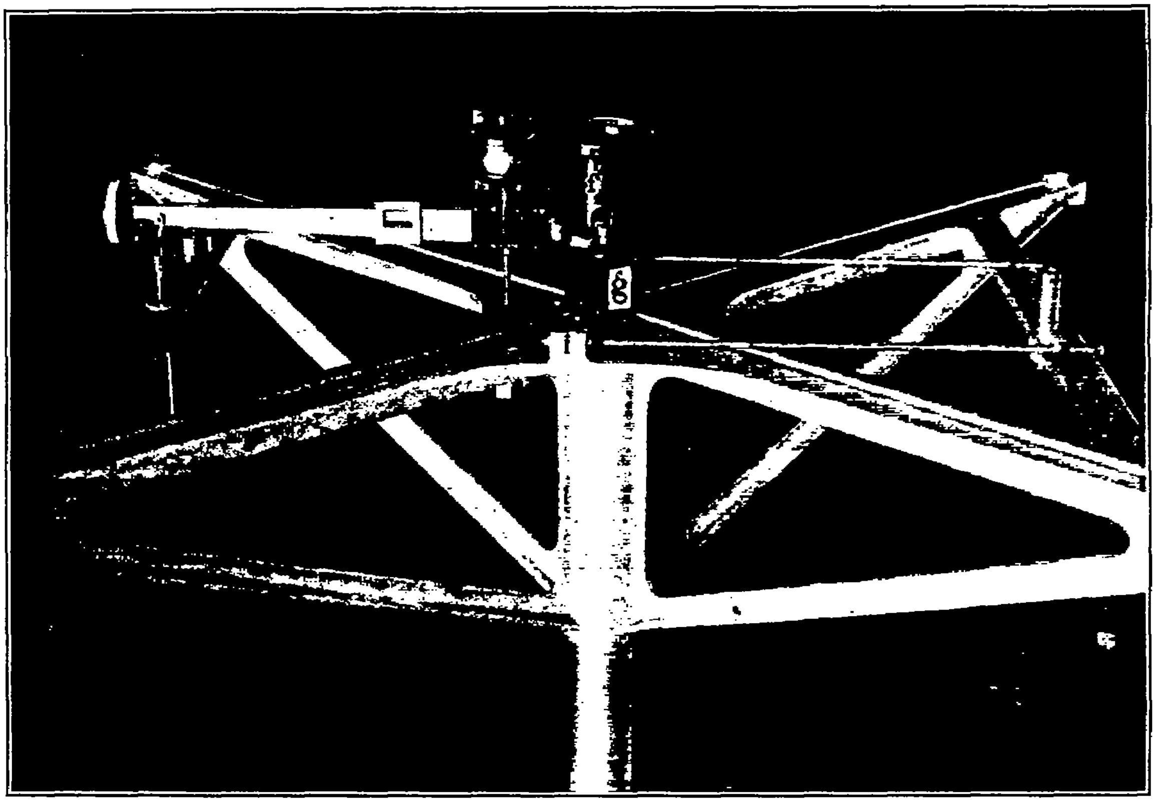


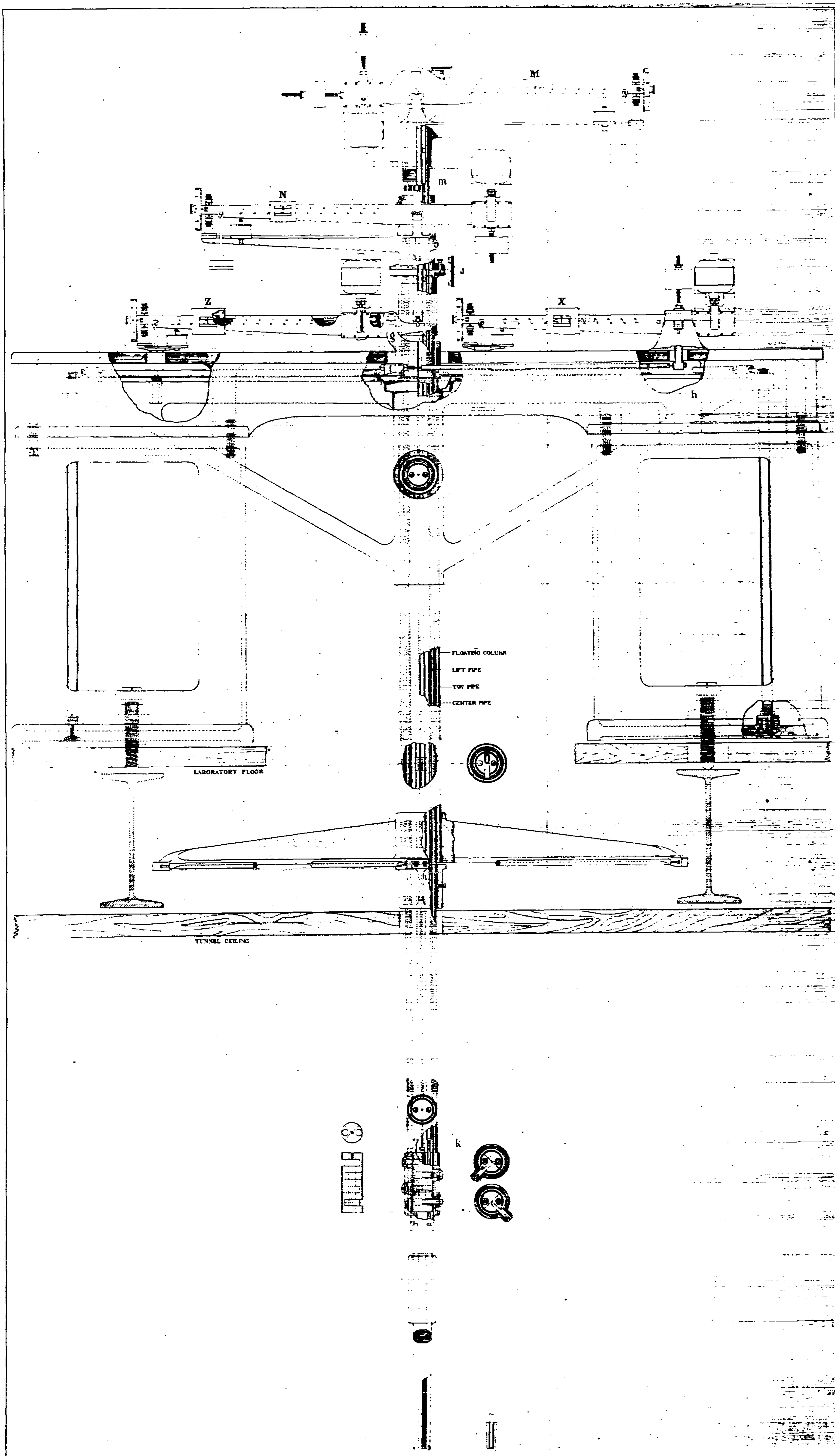
FIG. 5.—Wind balance lift mechanism.

parallel to the wind and anchored, 5 inches to either side of the lift pipe axis, to anchor lugs i. cast on top of the floating pyramid, as shown in figures 5 and 6. These rods prevent yawing of the pyramid, without restraining it across stream, and allow it to move along stream one five-thousandth of an inch when the tip of the drag beam kicks a thousandth.

The side drag is measured, as shown in the rear of figure 1, with another bell-crank system identical with the drag one, except that it has but one vertical finger and one pull rod, this rod running horizontally across the wind direction to an anchor lug on the floating pyramid.

In both drag mechanisms top-heaviness of the floating system is obviated by the elasticity of the four initially vertical supporting props, which overcomes the tendency of gravity to cause translation along and across stream when the props bend, however slightly. Furthermore the vertically moving counterweights could be made to modulate any such tendency, if it existed.

The accuracy of the force measurements is indicated under the caption, "Characteristic data."


M
N
m
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h
FLOATING COLUMN
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YON PIPE
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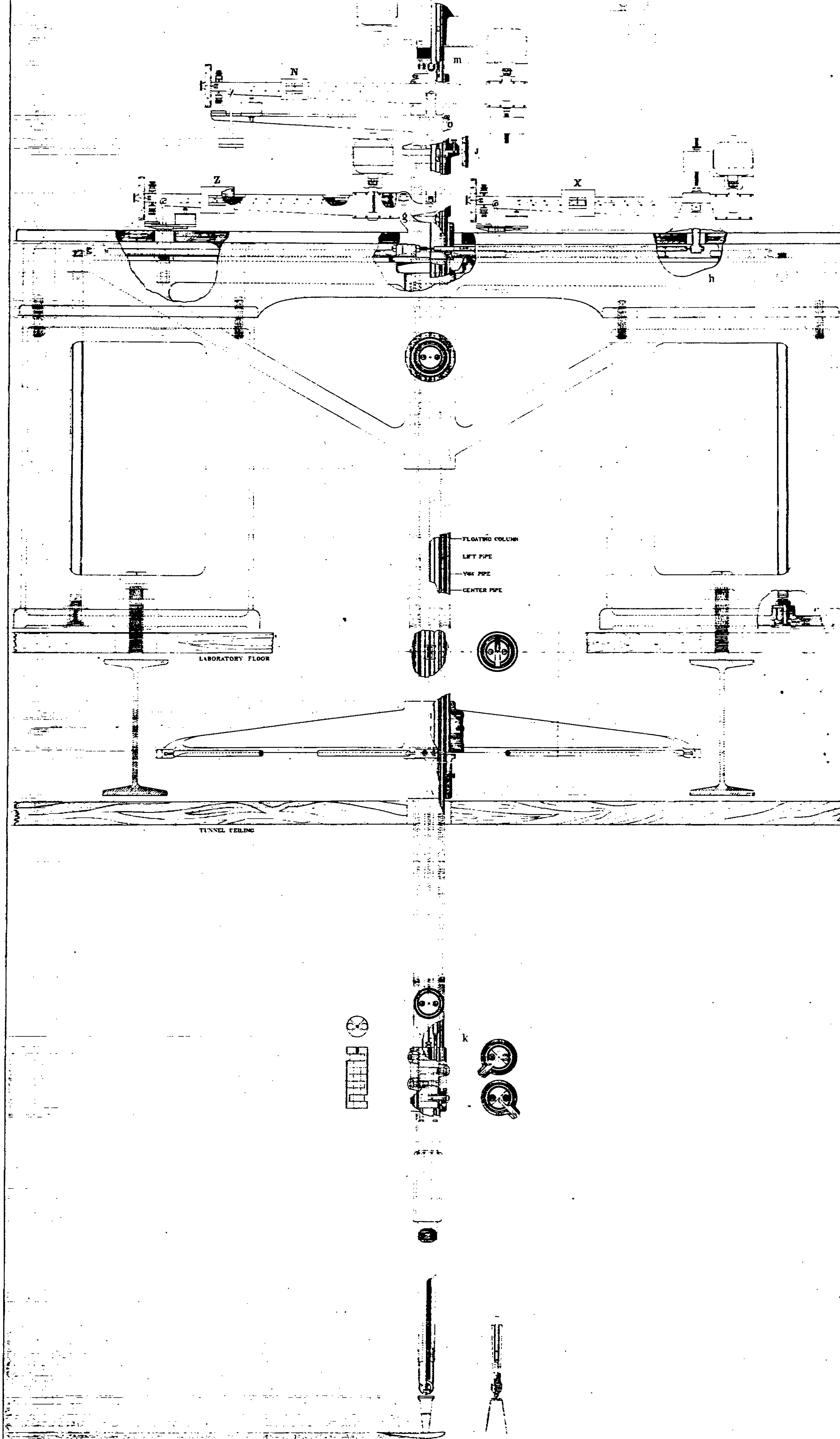

FIG. 6.—Wind balance assembly. Approximately ¼ full scale.

ROTATION MECHANISM.

Inside of the lift pipe rotates close-fittingly the "yaw pipe," figure 6, which projects half a foot above it and well below, extending to within half a yard of the center of the tunnel. Inside of the yaw pipe, as shown in the same figure, rotates without friction the "center pipe," protruding a few inches above and below it. The bottom of the center pipe has a conical socket which holds, as a drill spindle holds a drill, the rugged forged-steel tapering shank, half a yard long, which supports the model in the air stream. The yaw pipe when rotated in its plain friction bearings, by means of the worm wheel actuated by the micrometer disk *j*, shown in figure 6, sets the center pipe and all it carries at any desired angle of yaw truly to 0.01°. The yaw pipe also stiffens the center pipe, supports it in frictionless bearings, and carries the beam for weighing the yaw torque exerted on it by the wind force on the model.

The center pipe, when not rotationally restrained by its yaw lever, shown in figure 1, can oscillate many degrees within the yaw pipe, which latter in turn carries it along and across stream a small fraction of a thousandth of an inch, borne itself by the lift pipe and floating system. As shown in cross section, figure 6, four axial knife-edges pressing against four separate diametral facets of a ground-steel plug inside the center pipe near its bottom, and a like system near its top, prevent translation of the center pipe across the yaw pipe, which at each end supports the four radial bars whose edges constitute said knife-edges. Further, the center pipe is supported by a steel wire *k* running axially from the lower to the upper plug, and firmly fixed at its own center in a bridge-bar set diametrally across the yaw pipe and through an ample slot in the center pipe. With reference to the yaw pipe, therefore, the center pipe can have no motion but axial rotation, and this without perceptible friction or elastic resistance.

At the extreme top of the center pipe, figure 6, are knife-edge seats supporting the axle of the pitch beam. On this axle is an easy fitting worm wheel incased in a worm housing fixed to the axle and pitch beam. A narrow steel belt on the 1-inch diameter hub of this wheel runs, without perceptible contact or friction, down through large holes in the knife-seat plugs inside the center pipe, thence down through channels in the fore and aft edges of the shank, and passes over a 1-inch frictionless pulley having a down-reaching flange for supporting the streamline fork holding the wind model. The belt has a tooth at either pulley to prevent creeping and is thickened between the top and bottom pulleys sufficiently to prevent material stretching. This belt system can, with the wind on, be made to set the model to any desired pitch angle truly to 0.01°, while still remaining in ready condition to measure the pitching moment.

The more detailed working of the pitch belt on its lower pulley can be seen in figure 7. Firmly set in the bottom tip of the balance shank is the top lobe of an "Emory knife-edge" whose bottom lobe can rotate flexingly about the elastic axis 2° or 3° in pitch, positive and negative. The lower lobe is embedded in a coaxial grooved disk *l* which rotates with it until limited by buffer pegs in the tip of the shank. Enveloping this disk and coaxial with it is the lower belt pulley just described, which has an easy peripheral fit, and can be slid round the disk to alter the pitch of the model holder supported from its down-reaching flange.

Now suppose that initially the elastic knife-edge is in its unstrained position. When the belt moves, the pulley at first turns integrally with the disk and lower lobe, then slides about the disk after the latter bumps the stops. The pulley may continue, carrying the model through any desired pitch to ±90°, still sliding on the grooved disk which rests against the stops. A definite small reversal of the belt now brings the lobe of the knife-edge back to its unstrained position and allows frictionless vibration of the pulley-belt-and-pitch-beam system, if its tares are adjusted. As an alternative design, the buffer pegs can be made adjustable from the desk, so as to lock the Emory knife-edge during change of incidence, to prevent flexing, then release it for weighing.

In practice the knife-edges and tempered belts are amply free of friction and hysteresis, and together hold the model securely against all components of translation and rotation. The belts are kept suitably taut by turning the knurled ring nut *m* of figure 6, thereby sliding the top casting and its knife seats up or down the center pipe. In usual practice the stretch of the belt is negligible; in extreme loading the slight stretch is found by previous calibration.

Various other forms of axle for the lower pulley, such as plain journal, ball-bearing, plain knife-edge, etc., were included in the original design, but were held in reserve for special service should the need arise. Also, to prevent the lower disk lobes from straining under excessive yaw load, they can be locked to the shank tips with little key wedges temporarily inserted between them.

MEASUREMENT OF MOMENTS.

The yawing moment of the model is transmitted through the center pipe and its yaw lever, Figure 1, to the forked crank reaching up to it from the axle of the yaw weighing beam. Adjusting screws in the prongs of this crank fork fit the tip of the yaw lever truly to one-thousandth of an inch and transmit the moment to the yaw beam. The sliding of the weights by hand admits of true yaw measuring but disturbs the other weighings, a blemish that can be removed by using a motor. Otherwise the yaw mechanism is satisfactory. The resistance of the 50-pound yaw mechanism to rotational vibration was found to be so slight that with no wind the center pipe would oscillate nearly half an hour before coming to rest from a slight displacement. The pitching and rolling moments also can be truly measured when the lower belt pulley is well pivoted, and especially with the elastic knife-edge. The precision of these measurements is indicated under the caption "Characteristic data."

SMOOTHNESS OF AIR STREAM BELOW WIND SHIELD.

The parts of the balance within the air current are protected from drag by an enveloping stream line sheet-metal wind shield, the bottom of which contracts to a smaller shield which, as seen in Figure 3, closely incases the tapering shank. These shields cause some deviation of the lines of flow immediately about them, which, however, is immaterial 2 inches below the finer shield. The model is therefore always held well below this smaller wind-shield disturbance, where the flow, determined with the shields in place, is found by exploration with the incidence meter and pitot to be sufficiently uniform.

CORRECTION FOR MODEL HOLDER.

Protruding down from the shielded shank is the bifurcated model holder whose two prongs are each about 1 millimeter thick and very well stream lined, especially where they enter the surface of the model. Allowance for the wind effect on this holder must be made. The wind effort is measured first on the model and holder, then on the holder alone with the model detached but not removed. The difference is the effort on the model alone, for the proximity of the prongs causes no material disturbance of the flow past the model. To show this, dummy prongs were held near the model during measurement and were found not to affect the reading as they approached or receded. Each prong near the model can be shaped to have less than one-fifth the resistance of a round wire 1 millimeter thick and of the same length.

PROCEDURE OF MOUNTING AND MEASURING.

Before the model enters the tunnel it is tested on the plane-table micrometer to determine the degree of its conformance to the structural specifications. Then the two-prong holder is attached, usually near the "design" centroid, or point representing the centroid of the full-cale structure, and commonly on the less cambered side of the model, such as the flat sides of an aerofoil or the bottom of an airplane body. When the wind test is to start, the dove-tailed flange of the holder is slipped on the pulley flange at the bottom of the wind-balance shank. A light spirit level applied to the wing chord, or other reference line, serves to set the model at zero incidence. The reading of the pitch circle at the top of the balance is then set to zero, and the counterweights are adjusted on all the weighing beams to be used. Unless a special counterpoise to the model itself be used for gravitational balance at all angles of pitch, static weighings with the pitch beam are made, with no wind, for some pitch positions of the model. These readings can be omitted if the gravity moment of the model about the supporting pivot has been previously determined for a known position of the centroid. The

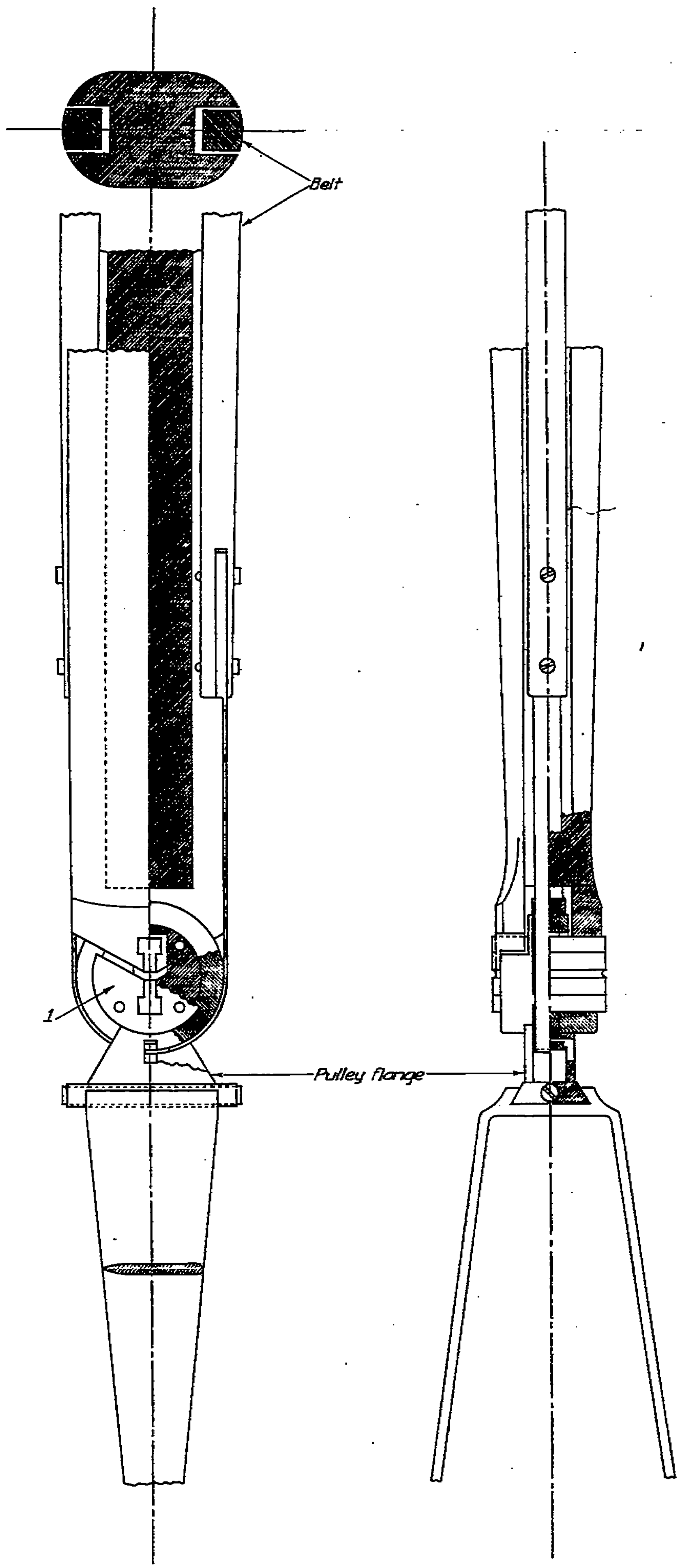

FIG. 7.—Wind balance, shank and model holder, full size.

wind is then set at the fixed speed desired, and note is made of the elastic distortion of the model, if perceptible, due to the wind load at various incidences. The apparatus is now ready for regular readings.

More commonly but three of the six components of the wind wrench, viz, the lift, drag, and pitching moment, are to be measured. The weighings are all made at once automatically, and require each but a minute for a fixed poise and wind. Holding the wind steady, one can give the model a new incidence, by turning the worm of the pitch circle, and proceed with the weighings as before. Or the poise of the model can be held while the air speed is given various fixed values. Finally the weighings are repeated with the model detached but not removed, as already explained. Thus, with the balance working normally, a complete set of weighings of lift, drag, and pitching moment, for one speed and sixteen angles of attack, can be made in less than half an hour. To accomplish as much with the old Eiffel balance required over eight hours, and gave data involving eight hours in the drafting room to deduce and plot the final values.

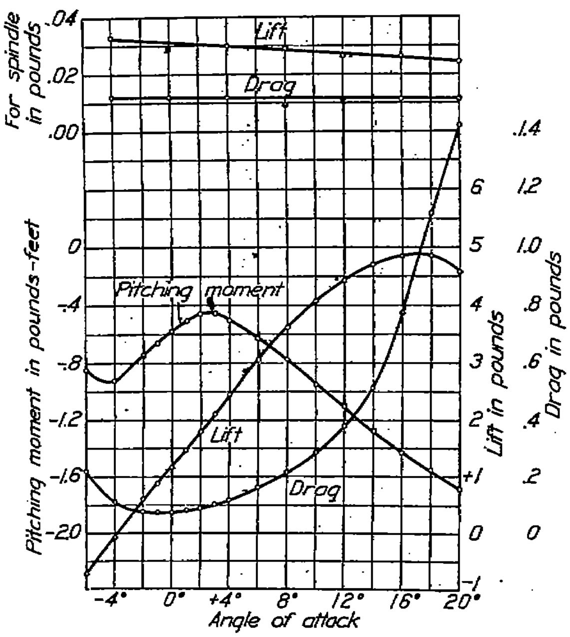

FIG. 8.—Characteristic sheet from six component wind balance, air speed, 40 M. P. H.

CHARACTERISTIC DATA.

The lower part of Figure 8 shows a typical set of uncorrected lift, drag, and pitching moment values, obtained by direct measurement on an aerofoil at 40 miles an hour and at the usual angles of attack for a practical test. The upper part of the plate gives the lift and drag for the holder alone, with the model detached but still kept in the positions it had in the first part of the run. These measurements are deducted from the lower ones as holder corrections for lift and drag. The like aerodynamic corrections for pitching moment were found to be negligible.

Referring to Figure 8, it is noteworthy that the moment readings are consistent to about 0.01 pound-inch; the force readings to 0.001 pound or less. The drag corrections are everywhere less than 15 per cent of the drag, and are measured truly to 1 per cent, or less, of the drag. The lift corrections are less than 1 per cent of the lift at incidences above 6°, and are measured truly to about 0.001 pound, the lift itself exceeding 3 pounds. For angles below 6° the precision for lift can be inferred from the corresponding part of the diagram. During calibration with standard weights the balance reads true to one-thousandth of a pound and pound-inch.

Measurements of the side drag, rolling moment, and yawing moment are not presented in this account. They can, however, be made with the same precision as those here illustrated.

ALTERNATIVE DESIGNS.

In addition to the present form of balance, various modifications or alternatives were sketched, or reduced to scale drawings.

For example, the "floating pyramid" was drawn with four supporting wires to be attached to the laboratory ceiling or to hollow standards erected upon the desk corners. The present more compact support allows free passage for an overhead traveling pulley.

Again the yaw pipe originally was omitted, and the center pipe was drawn gimbaled to the bottom of the lift pipe, within the tunnel, and free to rock slightly in roll and pitch, thus allowing the model six degrees of freedom. Six weighing beams were provided to measure simultaneously and independently the six components of the wind wrench. The yawing torque then was to be measured with a bell crank weighing beam riding on the pyramid and taking the tension of one of the drag rods, but graduated to read yawing moments directly.

The present instrument is adaptable to oscillation tests; and also may be provided with the more usual spindle for holding aerofoils by the end, as in the cross arm balance described in Report No. 138; or again may be used as a wire balance by an obvious modification of the lower portion of the concentric pipes.

Numerous means were devised for reading or recording the forces and moments. For example, revolution counters, one on each small motor, would indicate the weighings as effectively and accurately as do the graduated beams and disks. The movements of synchronous motors on a chronograph could be made to record all the individual weighings on a scale of any desired magnitude. Also the movements of the present disks and sliding weights can be recorded by well-known means. A description of these and numerous other details can better be given in a subsequent report.

HISTORY.

On May 18, 1917, two days after receipt of the Chief Constructor's request to develop a three-dimensional balance, the essential elements of the present instrument were formulated by the writer. These included a floating frame with three degrees of freedom, carrying a "lift pipe" inside which was pivoted a "rocking pipe," free to pitch and roll slightly, inside which was a spindle adapted to hold the model and set it in roll, pitch, and yaw. This frame-and-two-pipe mechanism gave the spindle six degrees of freedom, and was provided with as many weighing means for the independent measurement of the six components of wrench of the air force on the model. The motor weighing device was sketched in form for a preliminary test of its practicability.

These and various other schemes, roughed out at the time, were to the writer partly new and partly old. He had sketched the present desk feature with a four-wire frame some weeks previously, and a similar floating frame 15 years earlier. As the principle of motor weighing was old, there remained merely to prove by a preliminary experiment that forces ranging from 0.001 to 10 or more pounds could be measured with satisfactory speed and precision with the proposed automatic mechanism. The present pitch mechanism, devised some time later, also seemed to require preliminary test before the general construction should be recommended.

When, in April, 1918, my assistant, Mr. Louis Crook, became free to help with the preliminary tests, we mounted a small electric motor on a rough weighing beam and made it, by driving a weight to and fro, automatically establish and maintain equilibrium. After a few trials its operativeness was sufficient to indicate the practicability of a finished mechanism. To ascertain the feasibility of the pitch belt and pivots, we thought it more practical to make the finished parts at once, mount them on the Eiffel balance, and use them awhile. When this combination proved itself, the entire balance seemed practicable, and was developed as fast as Mr. Crook could find leisure, from his numerous other tasks, to make the working drawings. We computed together the more important dimensions to be sure of correct proportioning.

The general and detail drawings being well advanced, the main shopwork was done in the latter part of 1919 and the fore part of 1920, and the assembly was made in the spring, both under Mr. Crook's supervision. The final adjustments of the balance, the successful manipulation, and the proof of its capabilities for speed and accuracy were largely the work of Mr. R. H. Smith, the engineer in charge of the 8-foot wind-tunnel operations. He has shown that the instrument can save annually more than the cost of its construction.

CONCLUSION.

From the foregoing account it appears that the three-dimensional balance has the following properties:

1. It allows the model to be set quickly and accurately in roll, pitch, and yaw, without stopping the wind.
2. It can measure directly and independently the drag, side drag, and lift; also the rolling, pitching, and yawing moments.
3. It weighs all six components automatically, and easily can be made self-recording.
4. It can be adapted to oscillate the model in roll, pitch, and yaw, and to determine the damping coefficients.